

## THE IMPACT OF IUE ON BINARY STAR STUDIES

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### ABSTRACT

Every class of binary stars can be profitably studied with IUE, and for most of them, such observations are of fundamental importance, and have already yielded extremely valuable results or new surprising facts. Some of the classes are discussed in this review.

Atmospheric structure and wind complexes can now be studied, in binaries with supergiant components, much farther out in resonance lines of abundant elements. A hot component was discovered in  $\mu$  Sagittarii, and will probably enable us to study the atmosphere of the B8 Ia supergiant. A B-type companion to the F2 Ia supergiant in  $\epsilon$  Aurigae was found. A significant portion of the spectrum of the secondary component in  $\beta$  Lyrae was isolated. A whole class of objects was discovered with the IUE (the W Serpentis stars), bearing resemblance to  $\beta$  Lyrae. The radiation from these objects is probably largely produced in the process of accretion. Strong emission lines with P Cygni profiles suggest mass outflow driven by an induced stellar wind. A hot companion of the helium-rich star  $\upsilon$  Sagittarii was also discovered. We know now, thanks to IUE, that many if not all symbiotic stars are binaries, in which the hot component is probably a hot subdwarf. Valuable studies of the energy distribution and of gas streams in Algols are also reported.

### INTRODUCTION

I would like to claim that the two years of existence of IUE opened a new epoch in the studies of binary stars. Although the inevitable delay between observation and publication makes me unaware of many important results, what I know already demonstrates the enormous impact of IUE. The day when there will be no IUE or when we get no more time on it, will put us back by decades, and will be analogous to Galileo Galilei giving up his telescope and going back to Tycho Brahe's quadrants. Thus I should actually start and conclude my talk by first thanking every one and all of those who contributed to the success of the mission, and then immediately by asking: When do we start talking seriously about IUE 2, 3, ...n?

One proof of the enormous impact of IUE will be the fact that I will not be able to cover some important types of binary stars. My talk should be considered as a supplement to the excellent review talk given last year by Dupree (ref. 1). She talked mostly about binary stars with active chromospheres, i.e. the RS CVn stars and W UMa stars, also about X-ray binaries. I must also relegate the important topic of the cataclysmic variables and novae to other speakers at this symposium. Also, I can only mention here the increasing discoveries of blue companions to supergiants and Cepheids (ref. 31). They promise better determination of properties; however, they may imply much more.

## ζ AURIGAE AND VV CEPHEI STARS

Continuum observations in the ultraviolet are particularly important for binary systems in which one component is a hot star, much smaller in size than its mate. A classical example are the systems ζ Aurigae, 31 Cygni, 32 Cygni, and VV Cephei. The optical spectrum is completely dominated by a red supergiant, spectral type approximately K4 Ib for the first three, and M2 Ia for VV Cep. Hopelessly blended with the numerous deep metallic lines and/or molecular bands of the supergiant are the few lines signalling the presence of a B star: the Balmer lines and occasionally one or two He I lines. In VV Cep, the only signature of the hot component are (presumably) co-moving emission components of the Balmer H $\alpha$  and H $\beta$  lines. No wonder, then, that both the geometrical properties, masses etc. as well as the nature of the hot companions are poorly known.

These supergiant systems are famous because of the atmospheric eclipses: as the hot star travels behind the enormously extended atmosphere of the supergiant, the attenuated gases leave their imprints in the spectrum, and we can study individual layers in the atmosphere of a late-type supergiant. Orbital periods are very long, typically several years, so the eclipses are rare. The system with the longest period (20 years) among them, VV Cephei, was fortunately emerging out of eclipse in 1978-79, thereby providing a unique opportunity for IUE observers. Hagen et al. (ref. 2), Faraggiana and Selvelli (ref. 3, 4) and Dupree et al. (ref. 1) have already presented first reports on the sequence of changes in the emerging B spectrum. The system with the best determined elements, ζ Aurigae, had an eclipse at the end of 1979. I am confident that it was also adequately covered.

Far ultraviolet observations of the atmospheric eclipses are not mere supplements to optical data. Since many strong resonance lines are observable in the UV, the outermost atmospheric strata can be traced out much farther into space, and valuable data on stellar winds can be assembled. This also implies that such observations are not restricted to the phases adjacent to the eclipses. Thus, Stencel, Bernat and Kondo (ref. 5) have successfully studied 31 and 32 Cygni outside eclipse. The B star is of course not a passive test particle: it directly influences the supergiant atmosphere by its ionizing radiation. The system of 32 Cygni, poorly known from optical studies, is becoming a most interesting case, since the stars are closer together and the B star appears to move relatively deep in the outer layers of its mate. Stencel et al. (ref. 5) find a hot turbulent region near the B star, and a cooler, calmer, but faster moving wind farther out of the system. The spectrum is very rich in prominent emission lines with P Cygni profiles.

I would like to emphasize that the atmospheric eclipses should not be our only concern and interest in the supergiant systems. The supergiant stage of stellar evolution is short, so each such system provides a sensitive test of our theories of single star evolution or of double star evolution -- whichever prevails. Because of larger separations, the above-mentioned systems are more likely to follow the single star precept, but we will not be sure until the hot components are adequately observed. Are they really normal main sequence stars? Are their masses compatible with the observed differential evolution in the system? Only refined far UV studies can tell.

## $\mu$ SAGITTARI

One more question comes to mind in connection with the supergiant systems: Is the combination of a K-M supergiant and a B main-sequence star the only possible? Does nature discriminate against other combinations, or is it merely observational selection? Our most recent discovery in  $\mu$  Sagittarii speaks in favor of the observational bias.  $\mu$  Sagittarii is a luminous and fairly hot supergiant, B8 Ia. It is a 4th magnitude star in spite of a 1 mag. interstellar extinction. It has long been known as a single-line spectroscopic binary with a period of almost exactly half a year. I was most enticed by its large mass function,  $f(m) = 2.64$ . If the mass of the supergiant lies between 10 and 20 solar masses, as is reasonable to assume, then the invisible component must have 8 - 13 solar masses. When our search at Lick Observatory for a red component failed, we started observations in the far UV, using first Copernicus and then IUE. When a few lines suggesting a hot component showed on Copernicus spectra and the IUE short-wavelength spectrum appeared composite, some predictions could be made. Fortunately, the system is eclipsing. Elvey detected a shallow eclipse in 1938, but this must be the secondary eclipse, with the hot component in front. Therefore I predicted (ref. 6) that there must occur another and deeper eclipse in September 1979. The eclipse was indeed observed by Polidan with Copernicus, and by Guinan et al. optically and with the IUE.

Fig. 1 shows my August 1978 spectrum compared with Guinan's eclipse spectrum from September 1979. Their subtraction provides the beautiful spectrum shown in Fig. 2. This, then, is a newly discovered star, hot and bright, yet never before seen or even suspected. I think Fig. 2 is a tribute to the photometric qualities of IUE: we don't get a field of scattered points, but rather a nice, well-defined spectrum. From the steep slope of the continuum, and also from the absorption lines present, we conclude that the star is quite hot, about 40,000 K, and is probably an O star. Because of its mass, it should be a main-sequence object. Yet, again, let's be cautious until good radial velocities in the UV are obtainable and made. We will then have also a very valuable mass determination of a B8 Ia supergiant. If the companion does not have the characteristics we anticipate, we may also have another evolutionary puzzle.

The importance of this discovery may be more far-reaching. Polidan found additional absorption lines in the combined spectrum about a month before the September 1979 eclipse: therefore we may well have another atmospheric eclipse, but this time we will probe the outer atmosphere of a much hotter supergiant than in the "classical"  $\zeta$  Aurigae stars. The B8 Ia supergiant in  $\mu$  Sgr is known to have a pronounced stellar wind: here is the opportunity to study the wind complex.

## $\epsilon$ AURIGAE

Also unique among the supergiant systems is  $\epsilon$  Aurigae, in which we see an F2 Ia supergiant periodically eclipsed every 27 years by -- well, by something! The eclipse appears total but cannot be total since the same F2 spectrum remains. The depth of the eclipse appears to be essentially independent of the wavelength. Many exotic models have been invented ad hoc to explain

the nature of the mysterious invisible body, including of course an accreting black hole (which is still possible). Hack (ref. 7) suggested in 1961 that the eclipse is caused by a very extended atmosphere of a B star, which itself is not directly involved in the eclipses. Shortly after the successful launch of IUE, Hack and Selvelli (ref. 8) announced that they had indeed discovered a B star spectrum in the far UV. They find that the star has a temperature of about 15,000 K, radius only about  $2 R_{\odot}$ , and bolometric magnitude 7 mag. lower than the F supergiant. The star appears to be either at, or more likely somewhat below, the main sequence.

Thus, possibly, we now know the components in  $\epsilon$  Aurigae. However, considerable puzzle remains. The eclipse model postulates a huge ionized envelope, some  $850 R_{\odot}$  in radius around the B star, to act as a neutral semi-transparent screen. No other ordinary and modest B5 V star is known to have such an entourage. Hack and Selvelli suggest that perhaps the envelope was produced in a nova outburst of the hot star. However, postnovae do not look like B5 V stars. Moreover, what would be then the role of the F star? Just an accidental silent witness? More likely the supergiant plays a vital role in the system, perhaps as the ultimate source of the circumstellar material. Huang's (ref. 9) plausible idea of the eclipse being caused by a flat disk seen edge-on can be supplemented by the assumption that the disk is formed by accretion on the B star of the material flowing from the F star. This idea, already suggested by Morris (ref. 10) runs into the difficulty that the F star, although large (probably about  $175 R_{\odot}$ ), is still very much smaller than its critical Roche lobe. Perhaps we do not understand all the ways a supergiant can lose mass efficiently.

Although my remark will probably not apply to  $\epsilon$  Aurigae, I would like to caution that a thick disk can considerably obscure the light of the central star, but also that accretion can produce B-type continua simulating a genuine star. In any case, I bet that the next eclipse, due to start in 1982, will confront us with many surprises in  $\epsilon$  Aurigae -- if only we have an ultraviolet telescope then to watch the surprises.

#### $\beta$ LYRAE AND THE W SERPENTIS STARS

I would now like to elaborate on my last remark by discussing the group of interacting binaries which I named the W Serpentis stars. It includes  $\beta$  Lyrae, SX Cas, RX Cas, W Crucis, V 367 Cygni, AR Pavonis, and W Serpentis. These are eclipsing binaries of intermediate periods (13 to 605 days), long known for puzzling anomalies and discrepancies in their light- and radial velocity curves.  $\beta$  Lyrae was observed by Hack et al. (ref. 11, 12) with Copernicus, and found to have a unique spectrum in the far UV, essentially a set of strong emission lines. Optical observations also signal unusual properties. The only visible spectrum is B8 II, but the corresponding star is less massive than the other one which displays a continuum (since we observe two fairly deep eclipses) but no recognizable spectral lines. Again, special models were invoked, with or without a black hole, with the plausible justification that an extraordinary phenomenon calls for an extraordinary model.

Unique objects are undesirable. Almost in all cases, some vital information is not accessible, and cannot be replaced by inference from related objects

if these do not exist. Fortunately, we now know that  $\beta$  Lyrae is not a unique object. Within one short run in August 1978, R. H. Koch and myself found six binaries that have the same type of emission-line spectra in the far UV. This was not an accidental discovery. An important characteristic of the W Serpentis objects is the presence of emission lines (usually Balmer lines, in W Ser also He I, Fe II) in the optical spectra, which are incompatible with the optical continuum, belonging to a star too cool (A - G) to excite the emissions. It was therefore natural to search for a hotter source in the ultraviolet with the IUE. What we found (ref. 13) actually created more problems than it solved, but also showed that these systems are of considerable importance for our understanding of binary star evolution, in particular for understanding of accretion.

AR Pavonis appears to be a system showing the characteristics of both the W Ser stars and the symbiotic variables, and displays emissions of both types. For the other five stars, the far UV spectrum of W Serpentis shown in Fig. 3 is fairly representative. We observe strong emission lines of fairly highly ionized elements (N V, C IV, Si IV, Si III, Fe III, Al III, etc.) superposed on a relatively hot continuum. To trace this continuum is not easy because of the many emission lines, as well as deep depressions caused by severely blended strong absorptions. In W Ser, SX Cas, and  $\beta$  Lyr the estimated temperature of this continuum is, within about 1,000 K, approximately 11,500 K. The optically observed spectrum in  $\beta$  Lyrae (B8 II) corresponds to this temperature, but the observed hotter components in SX Cas (A6 III) and W Ser (F5 II) are much cooler than that. Only shortward of about 4,000 Å, our scans made at Lick Observatory with the IDS scanner indicate a weak contribution apparently coming from the hotter source seen in the UV. The ultraviolet continuum must therefore come from a region much smaller than the observed stellar surfaces.

Where in the system is the hot region located? Observations of the primary eclipse of SX Cas in February 1979 gave the answer. Optically, the eclipse is total. As my Lick scans confirm, the ordinarily seen A6 III disappears completely and is replaced by the spectrum of the cooler component, G5 III. At the same time, the UV hot continuum disappears as well, while the emission line spectrum is virtually unaffected (Fig. 4). Thus the hot source coincides with the hotter component in the system. W Ser, SX Cas, RX Cas, and  $\beta$  Lyrae are known to display unusually large period fluctuations and some other symptoms of rapid mass transfer. I suggest that the observed UV phenomena are associated with accretion. The hotter stars seen optically are the gainers in this process. Matter flows toward them from the secondary star, which presumably fills its critical Roche lobe. In an ordinary, short-period Algol semi-detached system (such as U Sge, U Cep), the stream impacts directly on the surface of the gainer. The W Ser systems have larger dimensions, so that the gainer is a smaller target, and the on-flowing material carries too much angular momentum. Therefore an accretion disk forms first (Fig. 5) and only its viscosity can eventually bring the gas particles inward to the surface of the accreting star. Thus we have an analogy to the accretion disks in the cataclysmic variables, but in the W Ser stars the accretion occurs on non-degenerate stars. We can scale the available models for cataclysmic variables (ref. 14) to estimate what kind of phenomena we will get in our case (ref. 15, 16). Most gravitational energy is released as a rule in a thin boundary layer between the disk and the surface of the accreting star, and I suggest that this

is the source of the UV continuum. In cataclysmic variables, the gainer is a white dwarf, so that this boundary lies at the bottom of a deep potential well, and soft X-ray emission is most likely to be emitted by it. For our main-sequence gainers, the potential well is much shallower, and the boundary layer will radiate most in the ultraviolet. In SX Cas, the observed temperature of the UV continuum requires a mass transfer rate of about  $2 \times 10^{-6} M_{\odot}/\text{year}$ , a plausible number which can easily be surpassed in other systems if the "case B" mass transfer is assumed. A preliminary estimate of the semi-thickness of the boundary layer indicates that it is about 0.06 of the radius of the A6 III gainer. However, more spherically symmetrical, albeit less dense clouds of gas must surround the gainer, since the observed A6 III spectrum is actually a shell spectrum, i.e. the absorption lines are formed in an extended atmosphere. In the model I am considering, the gainer has a radius of  $6 R_{\odot}$ , and the accretion disk could in principle extend as far as some  $30 R_{\odot}$ . There is no evidence, however, that a uniform, optically thick disk extends to any such distance, although some material is probably there and occasionally acts as a semi-transparent screen during secondary eclipses, which were in the past reported to be unusually long, but of variable duration. It is, however, also true that scaling up the models for cataclysmic binaries leads to a disk which is always geometrically quite thin perpendicularly to the orbital plane, with a maximum thickness of about only 1/10 of the star's radius; seen edge-on, such a disk would hardly cause more than a perturbation of the eclipse light curve. With the IDS scanner of the Lick Observatory, we also observed an "ultraviolet excess" of light shortward of  $4000 \text{ \AA}$  at the time when the UV continuum was eclipsed. I think this radiation may come from a "warm spot" formed at a place where the in-coming stream meets a denser accumulation of matter in the outer parts of the disk. This would then be an analogy of the famous "hot spot" observed in the cataclysmic variables, but on a more modest scale, because of the shallowness of the corresponding potential well and low density of the disk.

Now, let us ask the important question: How different is  $\beta$  Lyrae from, say, SX Cas? I can see two important but not fundamental differences. Firstly, the accretion disk in  $\beta$  Lyrae is really optically thick to a large distance from its center of gravity, and actually simulates a star (perhaps it is also geometrically much thicker than some theorists are willing to permit). All this may be due simply to a higher rate of mass transfer, which may well be two orders of magnitude larger than in SX Cas, i.e.  $10^{-4} M_{\odot}/\text{y}$  or thereabouts. Secondly,  $\beta$  Lyrae has an unusually hot and bright loser, which is a B8 II star. The integrated spectrum of the individual segments of the accretion disk cannot be assigned one definite temperature, but each spectral region can well be represented by one value of temperature -- and this temperature happens to be (accidentally) very close to that of the B8 II star probably everywhere in the accessible spectral range (ref. 12). The B8 II star appears to dominate the spectrum everywhere and the eclipses are only partial. Yet the case for the detection of the spectrum of the secondary (which may contain, in addition to the disk, also the genuine contribution of the accreting star if it is not completely hidden in the disk) is not hopeless, and some progress has already been made. Fig. 6 shows two spectra of  $\beta$  Lyrae, the lower taken during a secondary eclipse (i.e. the eclipse of the disk by the B8 II star). We notice a substantial reduction in the flux everywhere except in the region about  $1700 - 2200 \text{ \AA}$ , which behaves as if there were no

eclipse. The only reasonable explanation I have is that this region of the spectrum is dominated by overlapping emission lines of Fe III, which are formed well outside the eclipsed space. If we now subtract the two spectra, we get (Fig. 7) a fairly well-defined flat spectrum corresponding to a temperature near 10,700 K. I think this is the very first look anyone ever had at the spectrum of the mysterious secondary object in  $\beta$  Lyrae.

Perhaps we will also soon be able to better understand the mysterious absence of the absorption lines of the secondary from the spectrum of  $\beta$  Lyrae, a mystery augmented by the fact that this object is more massive than the visible B8 star. We know now that probably everywhere in the accessible spectrum, the continuum temperature of the disk is about the same, or only slightly lower, than the effective temperature of the B8 star. Thus the "effective spectral type" along the spectrum is always about B8 - A1. The very few strong lines appropriate for such a spectral type in the optical region must be badly blended with the same lines from the B8 star, and often, as in the case of the Balmer and He I lines, contaminated by emission on top of that. However, in the far ultraviolet many more lines are available, and I hope that our high-dispersion observations at the primary eclipse, planned for this summer, may well bring us a positive identification. The lines may, of course, be seriously washed out by the differential Keplerian rotation of the disk.

The strong emission lines observed in  $\beta$  Lyrae and all the W Serpentis stars remain a puzzle. As we saw in SX Cas (and also W Ser), their intensity is not significantly altered at any phase of the eclipse of the gainer. I wish we had the same coverage for secondary eclipses, and the rest of the orbital phases. Without this direct evidence, it is tempting to associate the emissions with the loser, which in SX Cas and RX Cas is a G giant. Since the observed emissions are indeed similar to those seen for example in Capella, a chromospheric origin appears the most simple and plausible explanation. Yet there are serious objections to this hypothesis. The power radiated in the emission lines in SX Cas is several solar luminosities, i.e. much larger than in Capella or in the considerably more powerful chromospheric emitters such as are the RS CVn stars (ref. 1, 17). Again, the N V line competes in strength with the C IV line or is stronger, while in giant chromospheres and in all parts of the transition region in the Sun, the C IV line is much stronger (ref. 18). And then, while it is easy to identify the potential carriers of the chromospheres in systems with G-type secondaries, where is this star in  $\beta$  Lyrae and V 367 Cygni?

Perhaps the most decisive argument comes from high-dispersion observations of  $\beta$  Lyrae. All emission lines are found to have pronounced P Cygni profiles (Fig. 8), although the low-dispersion spectra hardly show any indication of this (Fig. 9) -- which is a serious warning. The absorption components indicate an outflow at a velocity of about 150 km/s. Absence of most intercombination lines suggest a fairly high density of the line-forming region,  $N_e \approx 3 \times 10^{12} \text{ cm}^{-3}$ . The presence of fairly pronounced absorption components demands a fairly large depth of the formation region, and lack of eclipses suggests that this region is far outside the space actually swept by the two components. Radial velocity observations in  $\beta$  Lyrae with Copernicus (ref. 11,12) show that the emission lines, with a very few possible exceptions, do not participate in the orbital motion of either component. I think that both

the kinetic energy of this stellar wind as well as the ionization energy are ultimately derived from the gravitational energy released during accretion, but the actual mechanism of conversion is not clear. Is ionization maintained by a flux of soft X rays, generated in shocks near the gainer? Or is the ionization collisional? The amount of energy involved is not negligible, and the process must affect the evolution of the system: The line emitting region seems to have fairly high density ( $N_e = 3 \times 10^{12} \text{ cm}^{-3}$ ), it must be fairly thick to produce the absorption components, and its radius must also be quite large, as it probably lies outside the binary system. If the outflow is isotropic, fairly large mass loss from the system is indicated.

In order to test the isotropy of the outflow, I attempted to find non-eclipsing counterparts of the W Serpentis stars. The picture of the system may actually be less complex when it is not viewed edge-on, with all the accreting material obscuring the view of the accreting star. It may indeed be true that the gainer is easier to see, but the consequence appears to be that the emission lines are much less conspicuous against a stronger continuous background. The problem is also: how to find the non-eclipsing counterparts? I examined Be stars and shell stars with spectral peculiarities. The stars KX And (HD 218393), HD 51480, and HD 72754 were indeed found to have UV continua (including deep absorptions) quite similar to that of SX Cas. At least some emissions are weakly present (ref. 19). The last one of the three was reported to be similar to  $\beta$  Lyrae by Thackeray and Hutchings (ref. 20). The former two yield a good support to the claim made by myself and my collaborators (Harmanec, Kríž, Peters, Polidan - ref. 21) that a good model for Be and shell stars is that of an interacting binary system.

## υ SAGITTARII

Another bizarre object is  $\nu$  Sagittarii, a single-line spectroscopic binary with a period of 138 days. Its spectrum is famous for being extremely helium-rich and hydrogen-poor. A similar but much milder overabundance of helium with respect to hydrogen has been suspected in  $\beta$  Lyrae, and a certain degree of similarity indeed exists between these two objects. The invisible companion to the helium-rich star in  $\nu$  Sagittarii was detected with the IUE (Duvignau et al., ref. 22; Hack et al., ref. 23), and is probably an O9 V star. Rather surprisingly, the UV spectrum shows no emission lines. Possibly the period of rapid mass transfer is definitely over in this system.

## SYMBIOTIC STARS

This is a group of objects for which, in spite of considerable effort, non-controversial models were simply not possible without far ultraviolet observations. In the optical region, one observes a late-type continuum with superposed emission lines (H, He I, He II, C III, N III, some forbidden lines), which require a radiation source much, much hotter than the M or K star whose absorption spectrum is seen. Single and binary star models were proposed, and indeed both types may still apply, since the group is probably not homogeneous. However, the spectra I saw (AG Peg, AR Pav -- ref. 24, 25) and those described in literature (R Aqr, RW Hya -- ref. 26) fully justify their inclusion in my talk, since these stars are binaries. Z And (ref. 27) can almost certainly be added. This in itself solves a fundamental problem that



worried astrophysicists for decades.

An inspection of Fig. 1 in the paper by Keyes and Plavec in this volume shows why the dilemma was practically insolvable without UV spectroscopy: in the optical region, the hot component contributes virtually no radiation. The small "ultraviolet excess", and veiling of absorption lines observed shortward of about 5000 Å, is more likely due to free-free (and farther shortward to bound-free) radiation of hydrogen than to the hot component itself. (Incidentally, the figure I referred to is another testimony to the very good photometric performance of the IUE spectrographs. The diagram combines fluxes measured by the IDS scanner at the 120-inch Shane telescope of the Lick Observatory with those obtained with the IUE: they match without any artificial adjustment.)

In the symbiotics, the late-type component is an M or K giant, not a supergiant as in the  $\zeta$  Aurigae stars. Yet it dominates the optical spectrum, since the hot component is most likely a subdwarf, well below the main sequence. Bath (ref. 28) suggested that the UV continua may actually be due to the narrow accretion transition regions on ordinary stars, described here in the section on the W Serpentis stars. I think there is good evidence that the hot components are genuine hot subdwarfs; I believe that they may be products of case B mass transfer, and that the symbiotics are systems in which a little bit of cosmic justice takes place and the companion, which initially stole part of its mate's mass, is returning it back. Whether the subdwarf can accomodate it is questionable. In AG Pegasi, Keyes and myself find a similarity between the hot star and a WR nucleus of a planetary nebula. However, in the past century, the outflow from this star resembled rather an extremely slow nova. Yet it is likely that the ultimate source of activity is the M2 III companion. That star seems now to be much smaller than its Roche lobe. Apparently we do not understand a lot in this case, but when we eventually will, we may know much more about subdwarfs, planetary nebulae, and novae.

### THE ALGOLS

In the large class of the semi-detached binaries of the Algol type, the optical spectrum is dominated by the hotter, main-sequence component, but a certain degree of contamination (small in short period systems like U Sge and U Cep, large in longer-period ones like AW Peg and V 356 Sgr) does exist, due to the presence of the subgiant or giant, later-type loser. The IUE observations made so far by me and others will yield a more reliable determination of effective temperatures. Yet a more far-reaching program is conceivable. If the high-dispersion spectra are good enough to permit spectrum synthesis, one could profitably study the abundances and decide if they are anomalous. At the end of mass transfer, the loser's outer layers contain material partly processed inside the star. Will it be transferred to the gainer, or dispersed into space? We need this information badly in order to decide how much matter is transferred and how much escapes from the system.

Some more direct evidence on this topic is already being obtained from detailed studies of line profiles, which enable us to study gas streaming in the system (Kondo et al., ref. 29; Peters and Polidan, ref. 30). They claim that little is accreted; rather, the gas escapes or falls back on the loser.

## CONCLUSIONS

Although the IUE satellite has been operating for two years only, and the bulk of results and discoveries is still not accessible, it is already obvious that studies of all kinds of close binaries will profit considerably. I have surveyed only a limited number of types of interacting binaries. I have devoted a fairly large amount of available space to such exotic objects like  $\beta$  Lyrae,  $\epsilon$  Aurigae,  $\upsilon$  Sagittarii, W Serpentis, AG Pegasi, and AR Pavonis. I do not think that they are bizarre oddities far outside the mainstream of astrophysical research. On the contrary: each of them is trying to tell us something very important about the fundamental problems of stellar structure and evolution.

Let me formulate just a few of these problems.

(1) Do stellar black holes exist at all? If they do, do they play any significant role in stellar population -- or are they just bizarre freaks?  $\beta$  Lyrae,  $\epsilon$  Aurigae, and  $\upsilon$  Sagittarii were often in the past invoked as possible systems harboring a black hole. This hypothesis is all but abandoned now, but we should be quite sure.

(2) How are extremely helium-rich, hydrogen-poor atmospheres produced in binary systems?  $\beta$  Lyrae and, above all,  $\upsilon$  Sagittarii hold clues to the answer. Mass loss should bring He-rich material to the surface, but the theory does not predict any such extreme helium overabundance as has been reported for  $\upsilon$  Sagittarii.

(3) How are the subdwarfs in symbiotic stars related to cataclysmic variables? What actually determines that a star flares up as a dwarf nova (like Z And) or as a slow nova (like AG Peg)? Why is the subdwarf in AG Pegasi similar to the WR nuclei of planetary nebulae, and if it is, why did it flare up in the past century as a nova? How is a planetary nebula formed in a binary system? And why are all nuclei of planetary nebulae of the WN type, not WC (but AG Peg does not seem to be a pure WN)?

(4) The supergiant in  $\epsilon$  Aur and the giant in AG Peg are much smaller than their respective Roche lobes, and Reimers' formula gives a small rate of mass loss through stellar wind, too. Yet they appear to be the ultimate sources of all the activity and circumstellar mass. Where are we wrong?

(5) A fundamental problem of evolution with mass transfer in interacting binaries: How do the gainers accrete mass? Do they really swell all the way to their respective Roche lobes, as current theories postulate? Or can they reject the surplus material and drive it out of the system? How is it done? By exceeding locally the Eddington limit? Or does an instability occur, due to rapid rotation of the gainer? The W Serpentis stars, and  $\beta$  Lyrae in particular, promise all the answers.

After years of considerable effort, analyses based on optical data could not yield answers to our queries about the exotic systems, and in many cases a dead end was reached. IUE opened new horizons in a very dramatic way. We have now many more facts, and still more are within our reach. We should not retreat now. We need continued ultraviolet observations, perhaps even more refined: we need spectrograms calibrated both for spectrophotometry and for radial velocity work, and at sufficiently high dispersion.

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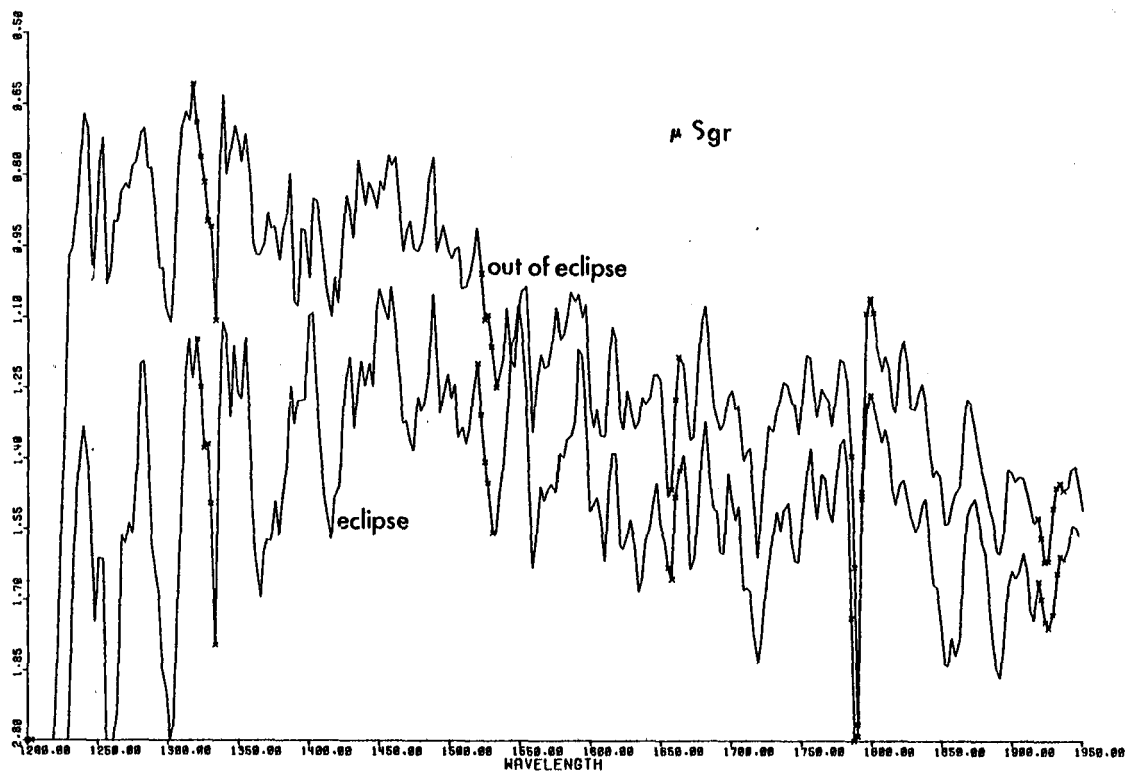


Fig. 1.: IUE spectra of  $\mu$  Sagittarii taken at primary eclipse and outside it.

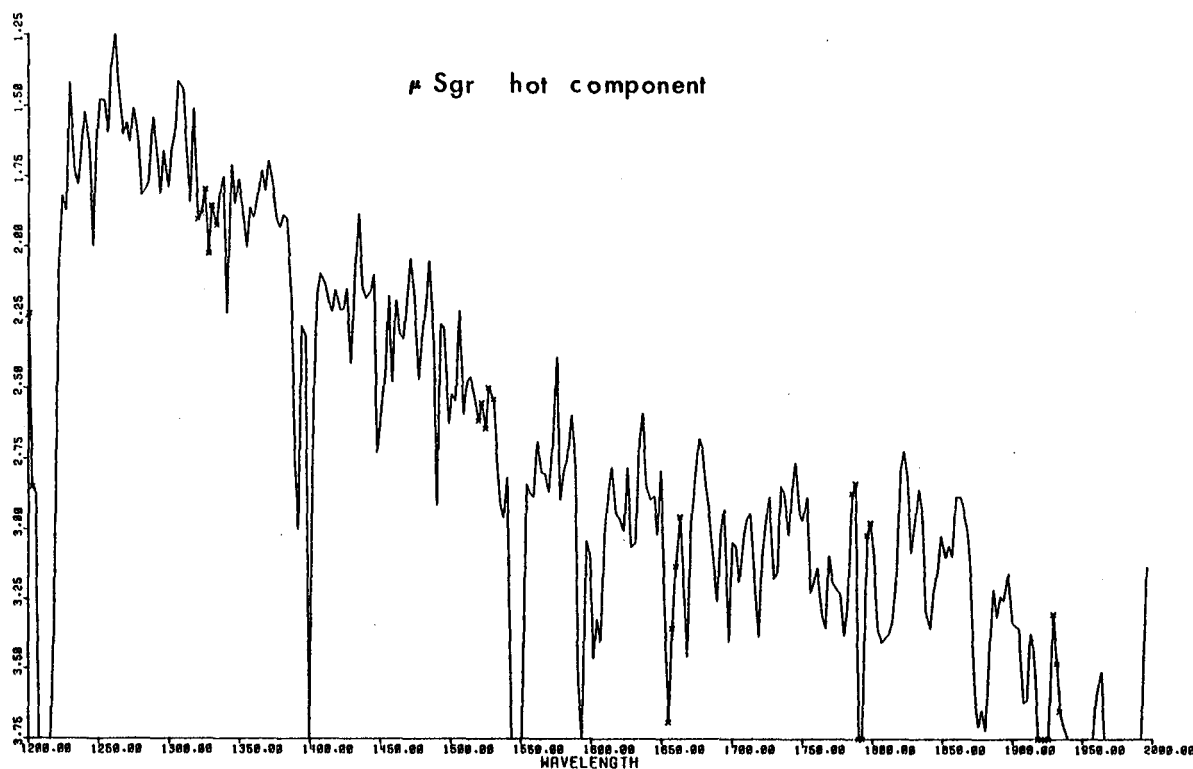


Fig. 2.: Reconstructed spectrum of the hot component in  $\mu$  Sagittarii.

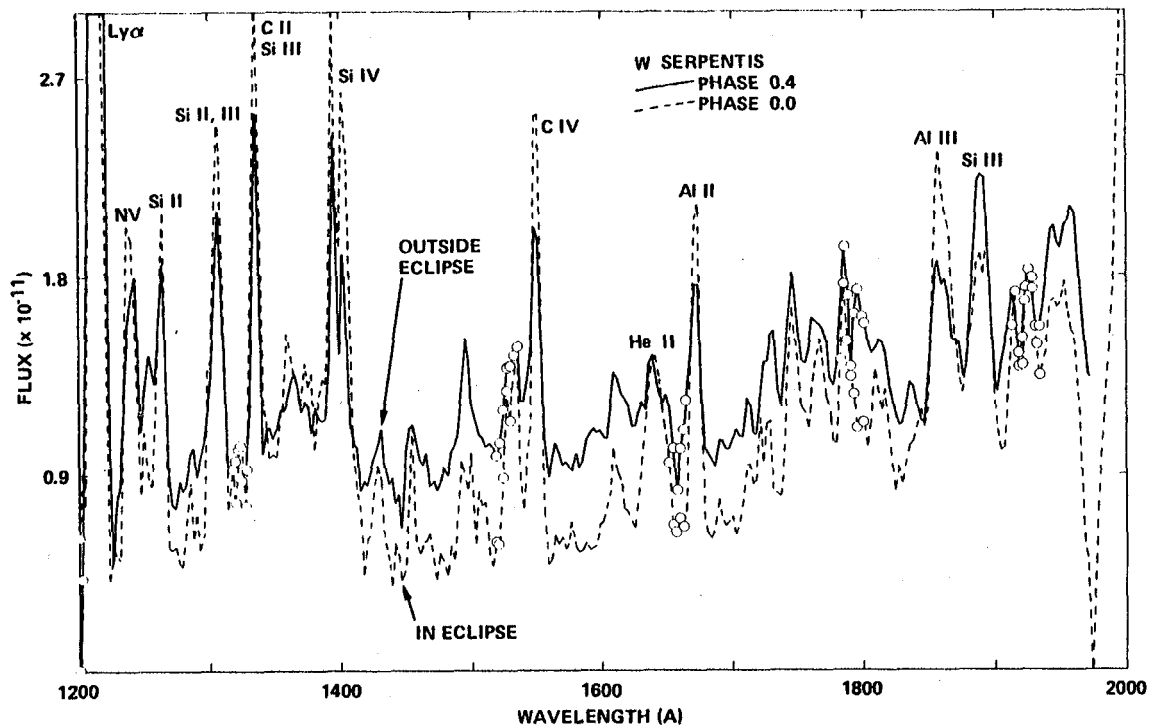


Fig. 3.: Far ultraviolet spectrum of W Serpentis.

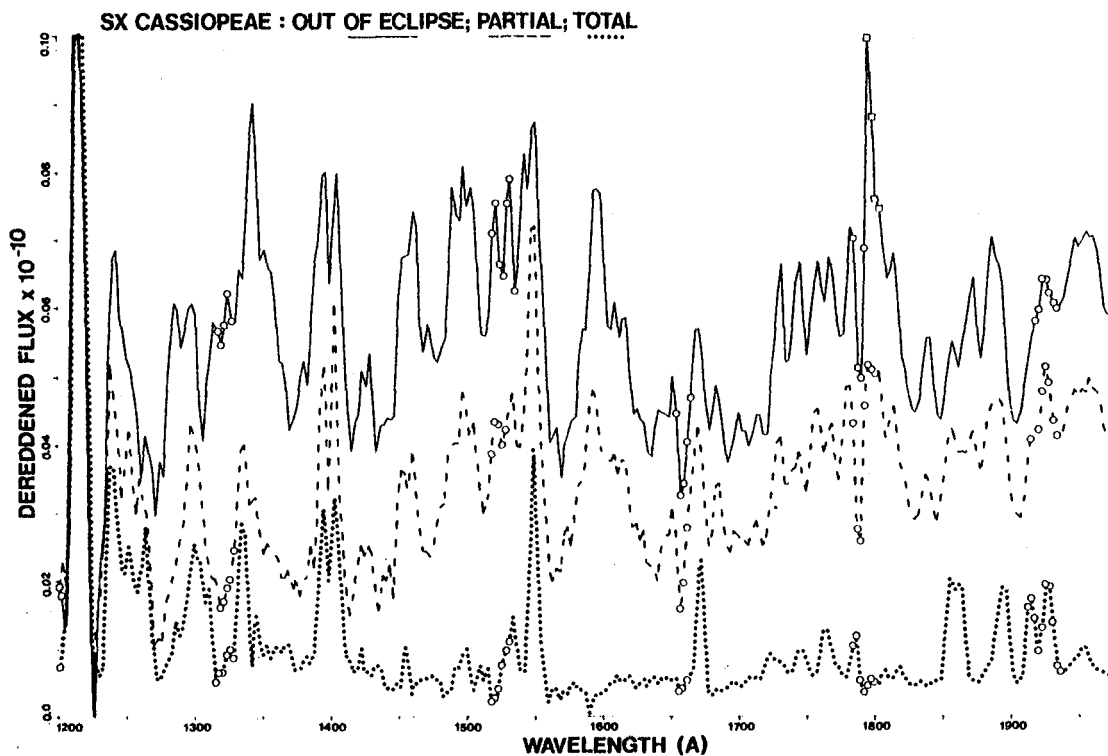


Fig. 4.: Far ultraviolet spectra of SX Cassiopeae taken during totality, during partial eclipse, and outside eclipse.

# SX CASSIOPEAE

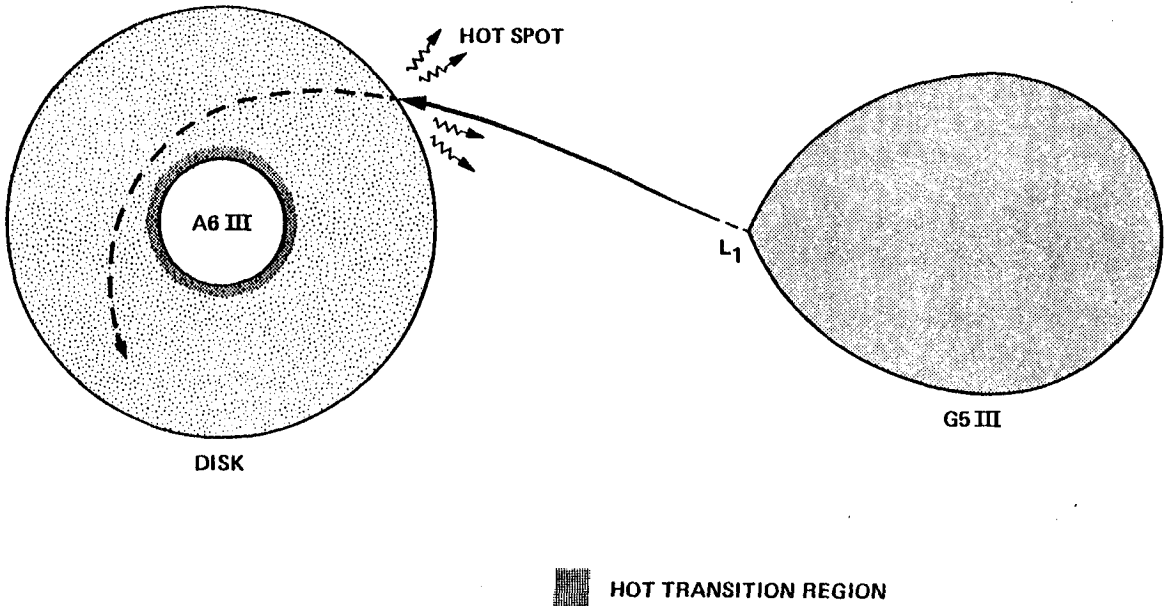


Fig. 5.: A schematic model of the system SX Cassiopeae showing disk accretion.

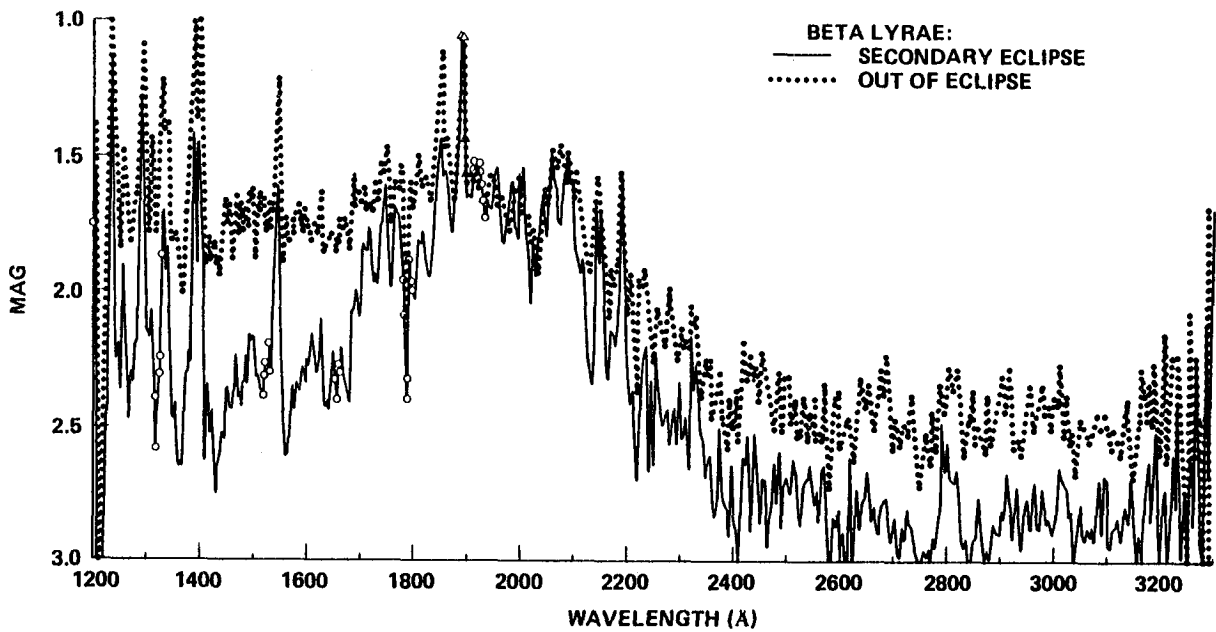


Fig. 6.: Ultraviolet spectra of  $\beta$  Lyrae, taken in secondary eclipse and outside eclipse.

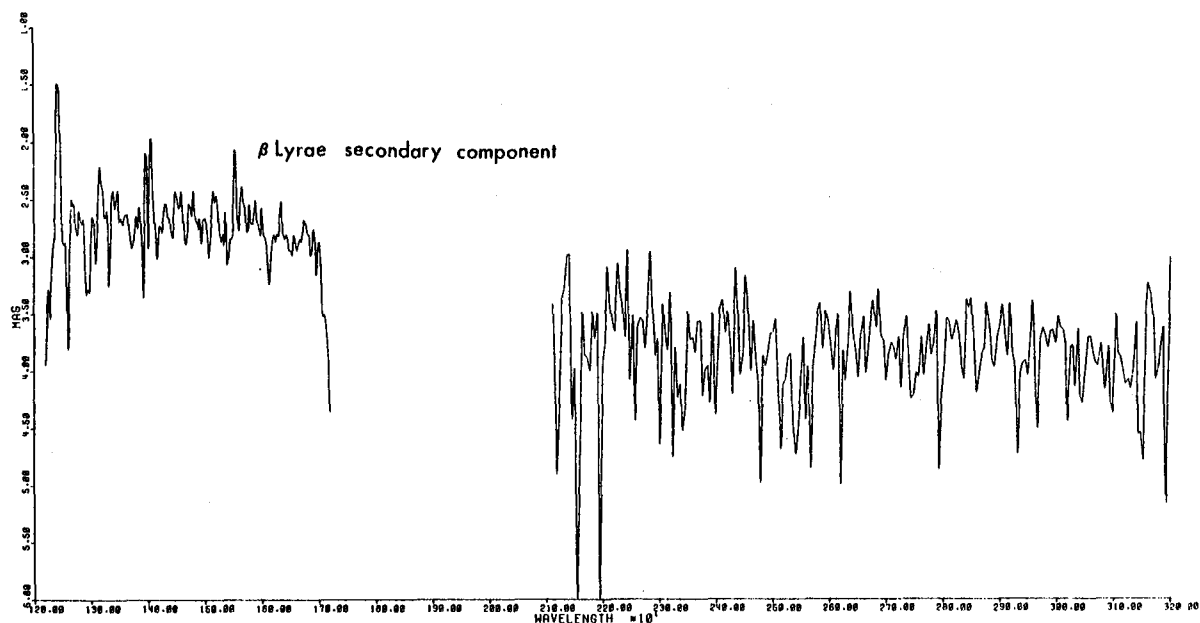


Fig. 7.: Reconstructed spectrum of the secondary component in  $\beta$  Lyrae.

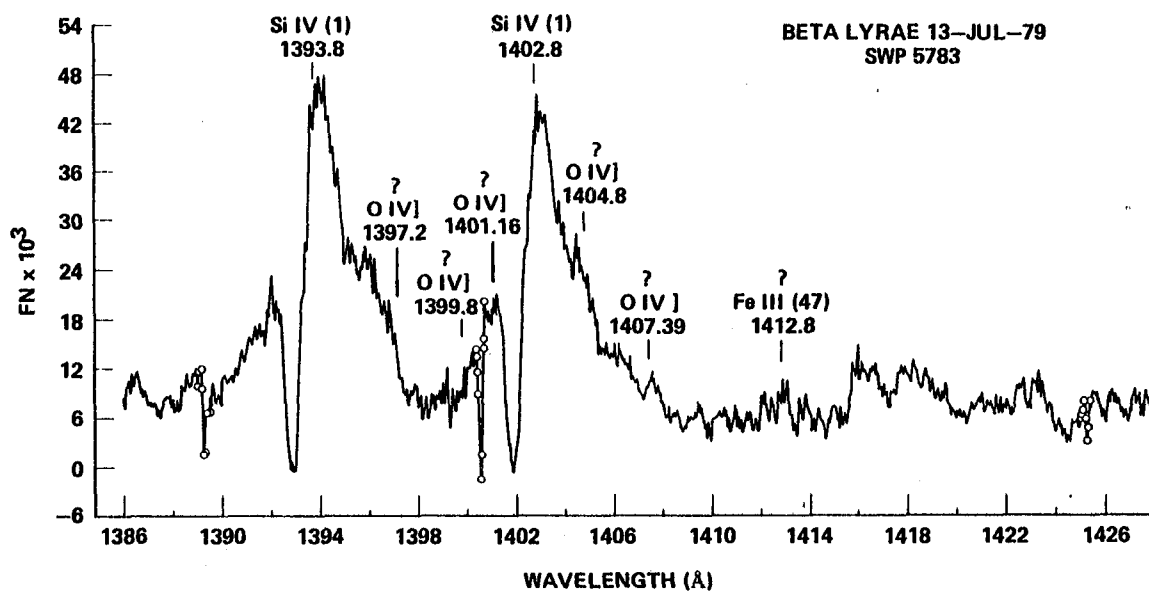


Fig. 8.: High-dispersion spectra of  $\beta$  Lyrae show P Cygni profiles of emission lines.



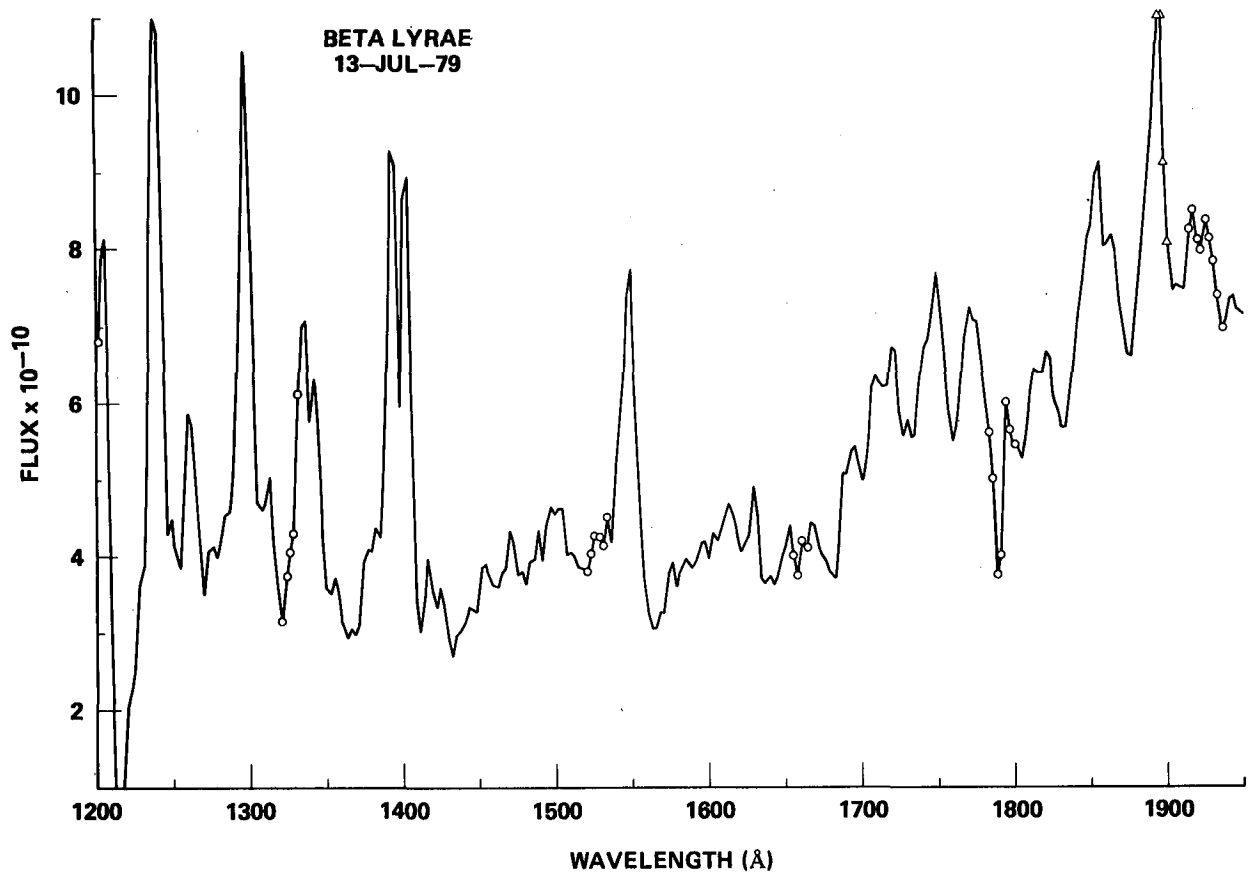


Fig. 9.: Low dispersion spectrum of  $\beta$  Lyrae shows virtually no trace of the P Cygni character of the emissions.